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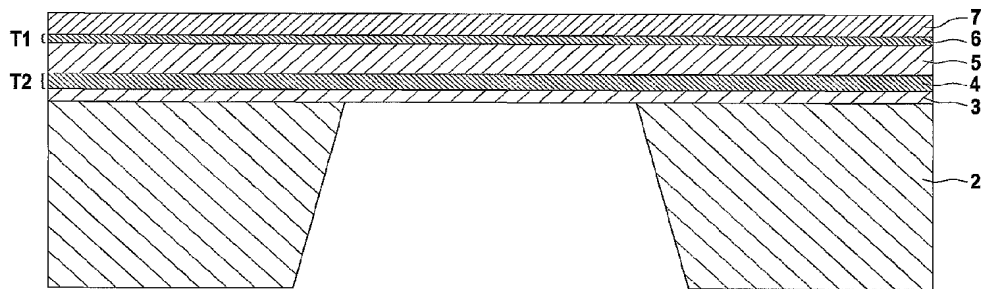
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(54) Title: ELECTRO-ACOUSTIC RESONATOR



(57) Abstract: An electro-acoustic resonator (1, 8, 17) of the membrane or FBAR type (1) or the solidly-mounted or SBAR type (8), with electrodes comprising a single conducting layer or multiple conducting layers, i.e. sandwich construction (17) with an optimum coupling factor k_r and thus an improved filter bandwidth. The optimum coupling factor k_r is achieved by the arrangement that the top electrode (6, 15, 25) is thinner than the bottom electrode (4, 13, 23). The coupling factor is independent of the resonator's layout defined by the mask.

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Electro-acoustic resonator

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The invention relates to an electro-acoustic wave resonator. Resonators are the basic building blocks of filters.

Thin-film bulk acoustic wave (BAW) resonator filters are of growing interest particularly for radio frequency (RF) front-end selectivity in wireless applications, e.g. 2G and 3G handsets. This technology offers the best possibility for integration and miniaturisation. One of the important parameters of an electro-acoustic resonator is its coupling factor k_r defined by $k_r^2 = [1 - (f_r/f_a)^2]$. In this equation f_r and f_a are the resonator's resonance and antiresonance, i.e. the frequencies of minimum and maximum impedance. Maximum achievable filter bandwidth is proportional to k_r^2 .

15 A BAW resonator consists essentially of a layer sequence comprising two electrode layers adjacent to a piezoelectric layer. For RF applications the piezoelectric layer typically consists of a deposited layer of a material such as aluminium nitride (AlN). For reducing deposition time, resonators with a feasibly thin piezoelectric layer are desired. The disadvantage of thin-film piezoelectric materials is their rather low coupling coefficient k_t . As resonator coupling factor k_r is proportional to the coupling coefficient k_t the design of the electro-acoustic resonator has to be optimised to compensate the rather low coupling coefficient k_t of thin-film piezoelectric materials. For example, a high coupling factor k_r is required for the 3G UMTS receive (RX) and transmit (TX) bands.

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WO 02/23720 A1 discloses a resonator that comprises a first electrode, a second electrode and a piezoelectric layer arranged between the above. A first acoustic compression layer is arranged between the piezoelectric layer and the first electrode with a higher acoustic impedance than the first electrode. For a warranty of a

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sufficiently low resistance of the electrodes that document reveals that the electrodes are at least 200 nm thick. There, the electrode preferably consists of Aluminium (Al) with a thickness of 300-600 nm. Such an electrode results in a low electrical resistance and effects only a small deterioration of the coupling coefficient achieved by the
5 arrangement of an acoustic compression layer.

US patent 6,051,907 discloses a method for tuning a thin-film bulk acoustic wave resonator (FBAR) located on a wafer. The method is used for fine tuning
10 if the centre frequency is different from a target value and is done by etching the top electrode. According to US 6,051,907 the structure of thin-film bulk acoustic wave resonators formed on wafers is altered before the wafer is diced. That method effects that the FBAR exhibits a series or parallel resonant frequency that is within an acceptable error margin of a design series or parallel resonant frequency, respectively. In
15 one example of US 6,051, 907 the top and the bottom electrode both comprise molybdenum (Mo) having a thickness of 300 nm. As the method for fine tuning in that document is based on thinning of the top electrodes of the FBARs, which results in increasing series resistance of the FBARs, there it is proposed to design top electrodes (of Mo) with a thickness of 400 nm and with a correspondingly thinner layer of
20 piezoelectric material, in this case zinc-oxide (ZnO).

The objective of the invention is to provide an electro-acoustic resonator which will give increased filter bandwidth.

This objective is achieved by an electro-acoustic resonator with a layer structure comprising a piezoelectric layer and a top and a bottom electrode layer, with
25 the thickness of the two electrode layers being unequal and with the top electrode layer being thinner than the bottom electrode layer. In this configuration maximum resonator coupling factor is achieved. The enhancement occurs due to an improved match, inside the piezoelectric layer, between the spatial distributions of the applied electric field (which is approximately constant in the direction normal to the layer) and the electric
30 field directly coupled to the acoustic wave (which is approximately cosinusoidal about a plane midway between thin electrodes, but closer to constant for optimal electrode

thickness).

The electro-acoustic resonator may be a solidly-mounted thin-film resonator (SBAR) or may have a membrane structure, also referred to as a film bulk acoustic wave resonator (FBAR). The layer sequence of an FBAR is typically etch-stop
5 layer / bottom electrode layer / piezoelectric layer / top electrode layer. The energy is confined by having a perfect reflector at the free-space interface above and below the resonator. The layer sequence of an SBAR is typically substrate / Bragg reflector / bottom electrode layer / piezoelectric layer / top electrode layer. The Bragg reflector comprises alternate high and low mechanical impedance layers and provides the
10 required reflection below the resonator. A mass-loading layer above the top electrode is included in a subset of the resonators in a typical filter design. The mass-loaded resonators have slightly lower f_r and f_a than the non-mass-loaded resonators. In all cases the resonant frequency is approximately inversely proportional to the thickness of the piezoelectric layer. For typical RF applications all layer thicknesses are of the order of
15 100 nm to 2000 nm. The substrate thickness is typically of the order of 0.1 mm to 2 mm.

At least one of the electrode layers of the electro-acoustic resonator can be formed by a stack of two (or more) conductive materials. Such a configuration is referred to here as a "sandwich" structure. The conductive materials have to be carefully
20 chosen as they influence the electrical loss and the bandwidth.

In one embodiment of the electro-acoustic resonator a conductive thin diffusion barrier is formed between the electrode layers.

In a further embodiment the conductive material in the stack that is in contact with the piezoelectric layer has a higher acoustic impedance than the conductive
25 material that is not in contact with the piezoelectric layer.

In another embodiment the conductive material in the stack that is in contact with the piezoelectric layer has a lower acoustic impedance than the outer conductive material that is not in contact with the piezoelectric layer. Preferably, the outer conductive material is a noble metal such as gold (Au) or platinum (Pt) which
30 protects the resonator's surface.

The conductive material with the lower acoustic impedance preferably

comprises aluminium (Al).

The conductive material with the higher acoustic impedance comprises for example platinum (Pt), wolfram (W), molybdenum (Mo), titan-wolfram (Ti_xW_{1-x} , $0 < x < 1$) or gold (Au).

5 The diffusion barrier between the electrode layers and /or between the electrodes may consist of titanium nitride (TiN) or titanium (Ti) or may consist of combinations of titanium nitride (TiN) and titanium (Ti).

For example, the inventive electro-acoustic resonator can be used in a filter with a centre frequency of 1,95 GHz. This is the centre frequency corresponding to
10 the transmission (TX) band of the UMTS 3G standard. For this application the bandwidth required is very close to the maximum achievable using aluminium nitride for the piezoelectric layer.

One preferred embodiment, for use in filters with centre frequency in the region of 2 GHz, is an electro-acoustic resonator whose electrode layers comprise
15 molybdenum with, for a resonant frequency in the region of 2 GHz, the top layer's thickness being in the region of 200 nm and the bottom layer's thickness being the region of 300 nm, these thicknesses scaling approximately inversely with resonant frequency.

Another preferred embodiment is an electro-acoustic resonator whose
20 electrode layers comprise platinum with, for a resonant frequency in the region of 2 GHz, the top layer's thickness being in the region of 50 nm and the bottom layer's thickness being in the region of 150 nm, these thicknesses scaling approximately inversely with resonant frequency.

The inventive electro-acoustic resonator may be used as a component of
25 a radio frequency (RF) filter, or as a component used in a sensor, or used in an ultrasonic transducer, or used in an array of ultrasonic transducers.

These and other aspects of the invention will become apparent from and will be elucidated with reference to the embodiments described hereinafter, where

Figure 1 illustrates a layer sequence in an FBAR,
Figure 2 illustrates a layer sequence in an SBAR,
Figure 3 illustrates a layer sequence in a sandwich SBAR,
Figure 4 illustrates a table with the coupling factor versus the
5 thicknesses of top and bottom electrode for a non-mass-loaded SBAR,
Figure 5 illustrates a table with the coupling factor versus the
thicknesses of top and bottom electrode for a mass-loaded SBAR,
Figure 6 illustrates a table with the coupling factor versus the
thicknesses of top and bottom electrode for a non-mass-loaded sandwich
10 SBAR,
Figure 7 illustrates a table with the coupling factor versus the
thicknesses of top and bottom electrode for a mass-loaded sandwich
SBAR.

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Figure 1 illustrates a layer sequence in an FBAR 1 consisting of, from bottom to top, a substrate 2, an etch-stop layer 3, a bottom electrode layer 4, a piezoelectric layer 5, a top electrode layer 6 and a mass-loading layer 7. The FBAR 1 shows the electrode layers 4, 6 with unequal thicknesses with the top electrode 6 having a thickness of T1 and the bottom electrode 4 having a thickness of T2. According to the invention T1 is smaller than T2. This asymmetrical arrangement enables the resonator to achieve maximum coupling-factor, thus giving maximum filter bandwidth.

Figure 2 illustrates a layer sequence in an SBAR 8 consisting of, from bottom to top, a substrate 9, an acoustic mirror 10 like a Bragg reflector comprising
25 alternate high 11 and low 12 mechanical impedance layers, a bottom electrode layer 13, a piezoelectric layer 14, a top electrode layer 15 and a mass-loading layer 16. The SBAR 8 shows electrode layers 13, 15 with unequal thicknesses with the top electrode 15 having a thickness of T3 and the bottom electrode 13 having a thickness of T4. According to the invention thickness T3 is smaller than thickness T4.

30 Figure 3 illustrates a layer sequence in a sandwich SBAR 17 consisting of, from bottom to top, a substrate 18, an acoustic mirror 19 like a Bragg reflector

comprising alternate high 20 and low 21 mechanical impedance layers, a bottom outer electrode layer 22, a bottom inner electrode layer 23, a piezoelectric layer 24, a top inner electrode layer 25, a top outer electrode layer 26 and a mass-loading layer 27. The sandwich SBAR 17 shows outer electrode layers 22 and 26 of equal thickness, and inner electrode layers 23 and 25 of unequal thickness with the inner top electrode 25 having a thickness of T5 and the inner bottom electrode 23 having a thickness of T6. Between the electrodes 22 and 23 and / or between the electrodes 25 and 26 there may be a diffusion barrier consisting of a layer of e.g. TiN or a combination of layers of Ti and TiN. This diffusion barrier is to avoid inter-diffusion of the two electrode materials 22 and 23 or 25 and 26 respectively. The thickness of the thin diffusion barrier is between 10 and 30 nm and does not change the performance of the resonator substantially.

The mass-loading layer (7 in Figure 1, 16 in Figure 2, 27 in Figure 3) is included in a subset of the resonators in a typical filter. The remaining resonators are non-mass-loaded.

The invention is illustrated by the example of a 1.95 GHz filter for the TX band of the UMTS 3G standard. For this application the bandwidth required is very close to the maximum achievable using aluminium nitride (AlN). In principle, a different optimum combination of layers is required for the mass-loaded and non-mass-loaded resonators. The optimum combinations are applicable to both ladder and lattice implementations of the filter.

Figure 4 illustrates a table with the coupling factor k_r versus the thickness T3 of the top electrode 15 and versus the thickness T4 of the bottom electrode 13 of the filter's non-mass-loaded SBARs 8 as shown in Figure 2. The electrode metal is molybdenum (Mo) which has about twice the acoustic impedance of aluminium nitride, and very high quality aluminium nitride layers can be grown on it. Tantalum pentoxide (Ta2O5) and silicon dioxide (SiO2) are employed as the high and the low impedance layers of the Bragg reflector. According to the table the optimum thicknesses of Molybdenum are seen to be in the region of T3 = 200 nm for the top electrode 15 and of T4 = 300 nm for the bottom electrode 13. For this combination the corresponding thickness of the aluminium nitride is 1410 nm, and the corresponding maximum value of k_r is 0,226.

Figure 5 illustrates a table with the coupling factor k_r versus the thickness T3 of the top electrode 15 and versus the thickness T4 of the bottom electrode 13 for the filter's mass-loaded resonators SBAR 8. The optimum thicknesses of the molybdenum also are seen to be in the region of T3 = 200 nm for the top electrode 15 and of T4 =
 5 300 nm for the bottom electrode 13 resulting in a maximum value of k_r of 0,222. The mass-loading layer thickness is 150 nm. Other layer thicknesses are the same as for the non-mass-loaded SBARs described in Figure 4.

The enhancement of the coupling factor k_r using the described optimum unequal thicknesses T3 and T4 should be even higher when wolfram (W) is used
 10 instead of molybdenum as wolfram has a mechanical impedance some 70% higher than that of molybdenum.

Filter implementation for the same centre frequency using sandwich SBARs is now considered.

Figure 6 illustrates a table with the coupling factor k_r versus the thickness
 15 T5 of the top electrode 25 and versus the thickness T6 of the bottom electrode 23 for the filter's non-mass-loaded sandwich SBARs 17. The outer electrode layers 22, 26 are of aluminium and the inner electrode layers 23, 25 adjacent to the piezoelectric (AlN) layer 24 are of platinum (Pt). To achieve an adequately low electrical resistance it is proposed that the aluminium layers 22, 26 have the same thickness, here set to 200 nm. The top
 20 25 and the bottom 23 electrode layers are the variables. Optimum coupling factor k_r is obtained with values of about T5 = 50 nm for the top electrode 25 and of about T6 = 150 nm for the bottom electrode 23 respectively. Between the electrodes 22 and 23 and / or between the electrodes 25 and 26 there may be a diffusion barrier consisting of a layer of e.g. TiN or a combination of layers of Ti and TiN. This diffusion barrier is to
 25 avoid inter-diffusion of the two electrode materials 22 and 23 or 25 and 26 respectively. The thickness of the thin diffusion barrier is between 10 and 30 nm and does not change the performance of the resonator substantially.

Figure 7 illustrates a table with the coupling factor k_r versus the thickness
 T5 of the top electrode 25 and versus the thickness T6 of the bottom electrode 23 for the
 30 filter's mass-loaded SBARs 17. Optimum coupling factor k_r is again obtained with values of about T5 = 50 nm for the top electrode 25 and of about T6 = 150 nm for the

bottom electrode 23 respectively. Other layer thicknesses are the same as for the non-mass-loaded sandwich SBARs described in Figure 6.

In both mass-loaded and non-mass-loaded sandwich SBARs optimum thicknesses of the inner Pt electrodes are almost independent of the thicknesses of the Al outer electrodes 22, 26. For optimum Pt layer thicknesses and Al layer thicknesses of 100 nm, 200 nm and 300 nm the coupling factor $k_r = 0,220, 0,216$ and $0,202$ respectively.

The invention may be summarised by a thin-film bulk acoustic wave resonator (1, 8, 17) of the membrane or FBAR type (1) or the solidly-mounted or SBAR type (8), either with single layer electrodes (1,8) or of the multiple-layer electrode sandwich construction (17), with an optimum coupling factor k_r , and thus increased bandwidth in filters incorporating such resonators . The optimum coupling factor k_r is achieved by the arrangement that the top electrode (6, 15, 25) is thinner than the bottom electrode (4, 13, 23). The coupling factor is independent of the resonator's layout.

CLAIMS:

1. Electro-acoustic resonator (1, 8, 17) with a layer structure comprising a piezoelectric layer (5, 14, 24) and a top (6, 15, 25) and a bottom (4, 13, 23) electrode layer, with the thickness (T1, T2, ...T6) of the two electrode layers being unequal, characterised in that the top electrode layer (T1, T3, T5) is thinner than the bottom
5 (T2, T4, T6) electrode layer.
2. Electro-acoustic resonator (1, 8, 17) as claimed in claim 1, characterised in that the electro-acoustic resonator (1, 8, 17) is a solidly-mounted resonator or SBAR (8,17) or that it has a membrane structure FBAR (1).
10
3. Electro-acoustic resonator (1, 8, 17) as claimed in one of the foregoing claims, characterised in that at least one of the electrode layers (25, 26 or 22, 23) is formed by a stack of conductive materials.
- 15 4. Electro-acoustic resonator (1, 8, 17) as claimed in one of the foregoing claims, characterised in that between the electrode layers 22 and 23 and /or 25 and 26 a conductive thin diffusion barrier is formed.
5. Electro-acoustic resonator (1, 8, 17) as claimed in claim 3, characterised
20 in that in the stack the conductive material (23, 25) that is in contact with the piezoelectric layer (24) has a higher acoustic impedance than the conductive material (22, 26) that is not in contact with the piezoelectric layer (24).
6. Electro-acoustic resonator (1, 8, 17) as claimed in claim 3, characterised
25 in that in the stack the conductive material (23, 25) in contact with the piezoelectric

layer (24) has a lower acoustic impedance than the conductive material (22, 26) that is not in contact with the piezoelectric layer (24).

7. Electro-acoustic (1, 8, 17) resonator as claimed in claim 5 or 6,
5 characterised in that the conductive material with the lower acoustic impedance comprises Aluminium (Al).
8. Electro-acoustic resonator (1, 8, 17) as claimed in claim 5 or 6,
characterised in that the conductive material with the higher acoustic impedance
10 comprises platinum (Pt), wolfram (W), molybdenum (Mo), titan-wolfram (Ti_xW_{1-x} , $0 < x < 1$), Gold (Au).
9. Electro-acoustic resonator (1, 8, 17) as claimed in claim 5 or 6,
characterised in that the diffusion barrier between the electrode layers 22 and 23 and
15 /or between the electrodes 25 and 26 consists of titanium nitride (TiN), or titanium (Ti), or consists of combinations of titanium nitride (TiN) and titanium (Ti).
10. Electro-acoustic resonator (1, 8, 17) as claimed in one of the foregoing
claims, characterised in that the electrode layers (4, 6, 13, 15, 23, 25) comprise
20 Molybdenum (Mo) and that, for a resonant frequency in the region of 2 GHz, the thickness (T1, T3, T5) of the top Molybdenum layer (6, 15, 25) is in the region of 200 nm and the thickness (T2, T4, T6) of the bottom Molybdenum layer (4, 13, 23) is in the region of 300 nm, these thicknesses scaling approximately inversely with resonant frequency.
- 25 11. Electro-acoustic resonator (1, 8, 17) as claimed in one of the foregoing
claims, characterised in that the electrode layers (4, 6, 13, 15, 23, 25) comprise
platinum (Pt) and that, for a resonant frequency in the region of 2 GHz, the
thickness (T1, T3, T5) of the top platinum layer (6, 15, 25) is in the region of 50 nm
30 and the thickness (T2, T4, T6) of the bottom platinum layer (4, 13, 23) is in the

region of 150 nm, these thicknesses scaling approximately inversely with resonant frequency.

12. Use of an electro-acoustic resonator (1, 8, 17), especially an electro-
5 acoustic resonator as claimed in claim 1, as a component of a radio frequency (RF) filter, or as a component used in a sensor, or used in an ultrasonic transducer, or used in an array of ultrasonic transducers.

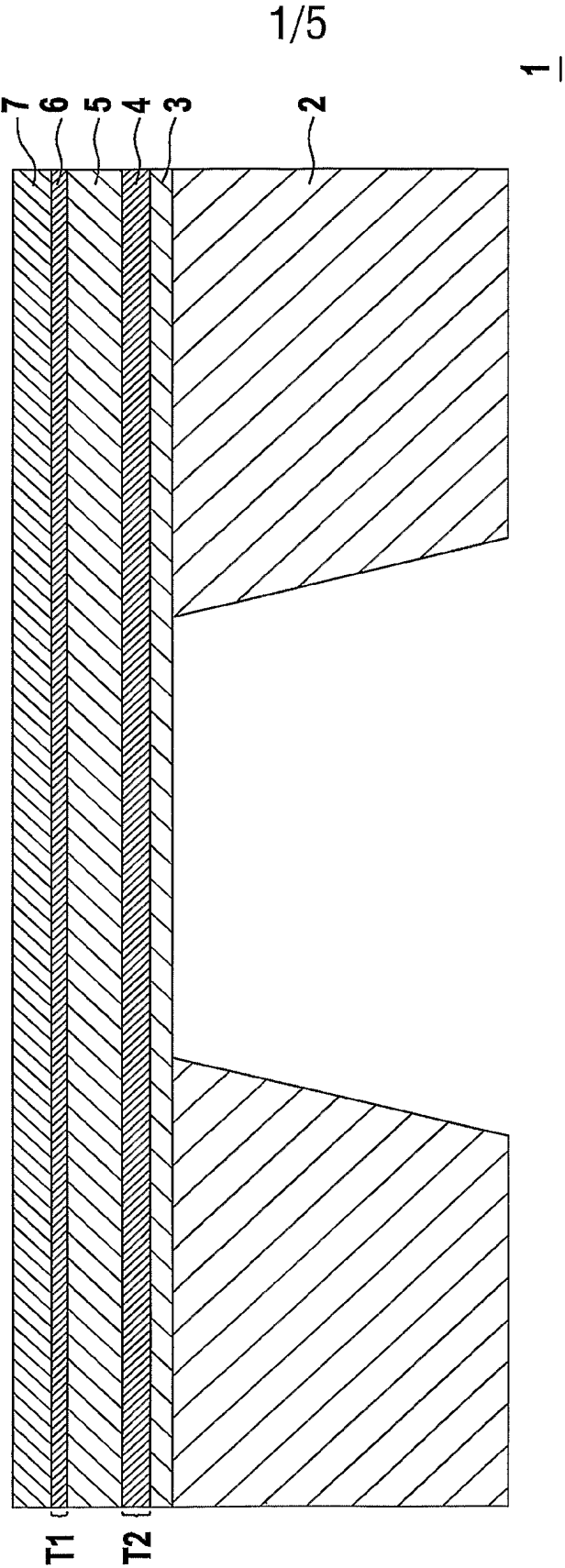


FIG.1

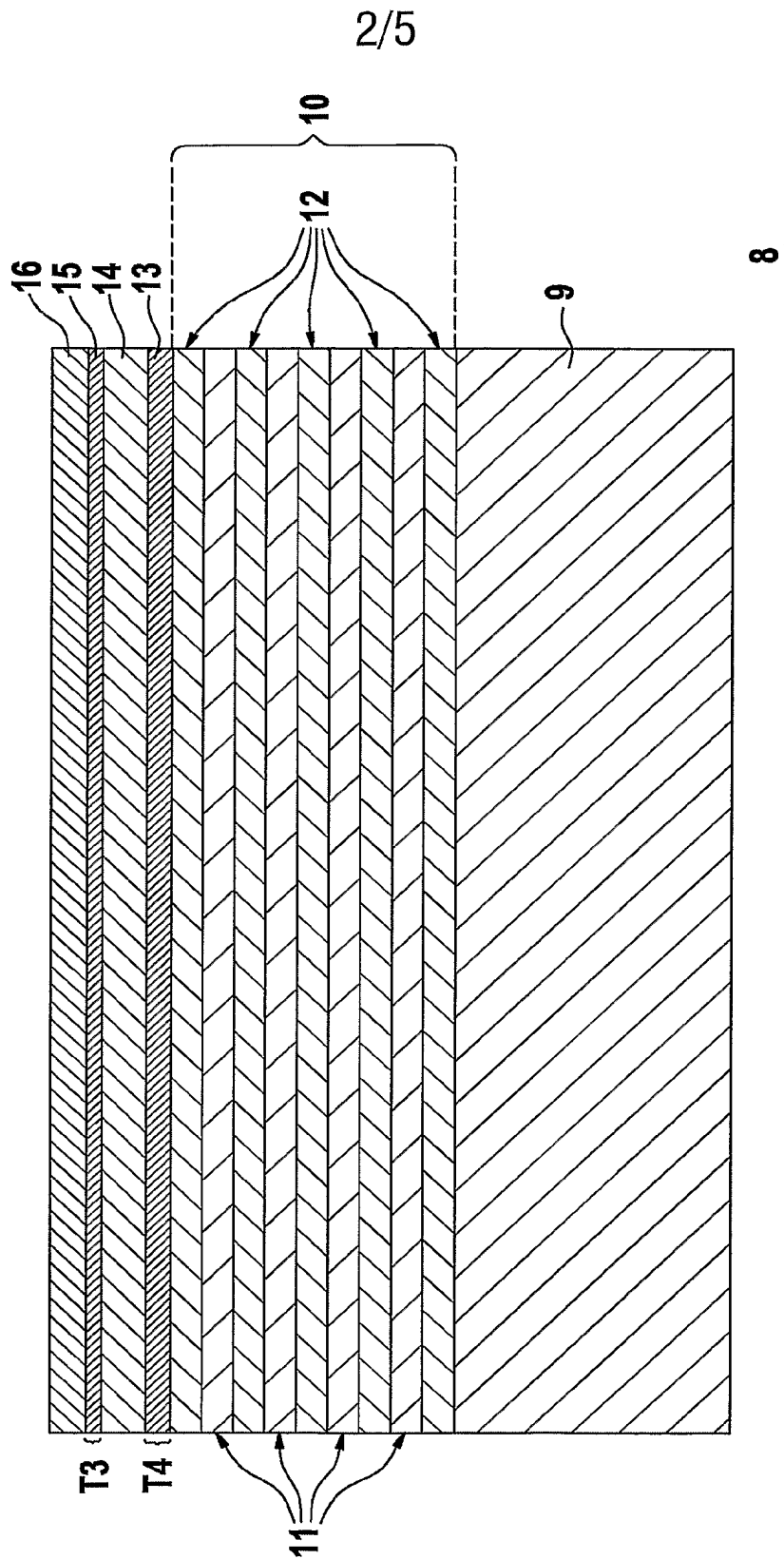


FIG.2

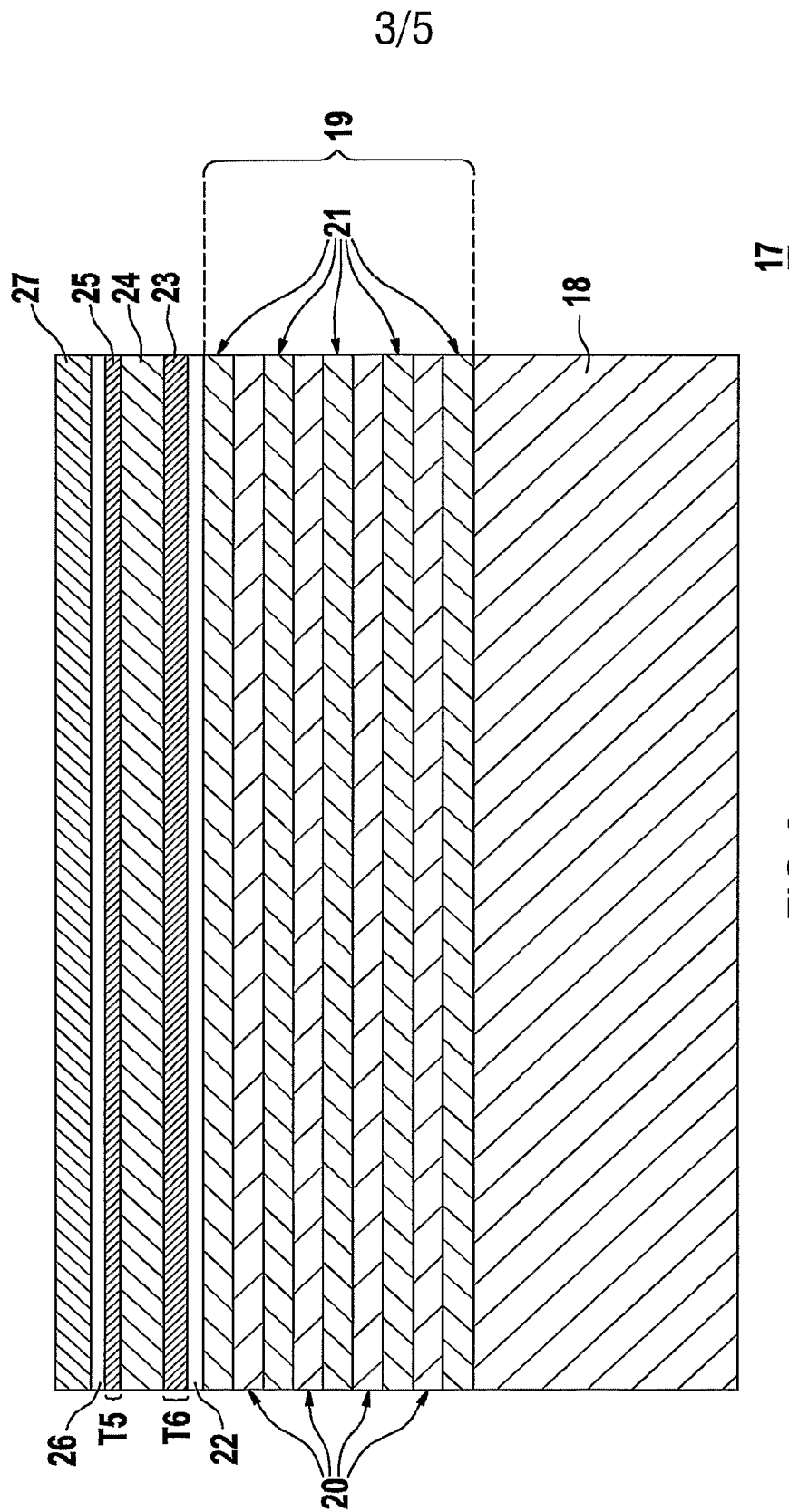


FIG.3

	T3 T4	50 nm	100 nm	150 nm	200 nm	250 nm	300 nm
	100 nm	0,216	0,219	0,218	0,218	0,212	0,208
	150 nm	0,216	0,219	0,223	0,218	0,219	0,216
	200 nm	0,220	0,224	0,222	0,224	0,224	0,220
	250 nm	0,216	0,219	0,224	0,226	0,219	0,216
	300 nm	0,223	0,226	0,224	0,226	0,218	0,223
	350 nm	0,214	0,218	0,224	0,226	0,218	0,214
	400 nm			0,223	0,217	0,217	0,213

FIG.4

	T3 T4	50 nm	100 nm	150 nm	200 nm	250 nm	300 nm
	100 nm	0,214	0,216	0,216	0,214	0,212	0,209
	150 nm	0,218	0,219	0,219	0,218	0,216	0,213
	200 nm	0,219	0,222	0,222	0,221	0,218	0,214
	250 nm	0,221	0,223	0,223	0,222	0,219	0,217
	300 nm	0,221	0,223	0,223	0,222	0,219	0,217
	350 nm	0,219	0,223	0,223	0,222	0,219	0,217
	400 nm			0,222	0,221	0,218	0,216

FIG.5

T5 T6	0 nm	50 nm	100 nm	150 nm	200 nm	250 nm
	0,204	0,202	0,198	0,191	0,191	0,181
50 nm	0,207	0,212	0,208	0,203	0,194	0,192
100 nm	0,209	0,216	0,211	0,204	0,204	0,194
150 nm	0,209	0,216	0,211	0,213	0,203	0,192
200 nm	0,213	0,211	0,216	0,208	0,196	0,183
250 nm	0,207	0,214	0,208	0,199	0,185	0,171

FIG.6

T5 T6	0 nm	50 nm	100 nm	150 nm	200 nm	250 nm
	0,204	0,204	0,198	0,191	0,184	0,177
50 nm	0,212	0,212	0,208	0,201	0,194	0,186
100 nm	0,214	0,216	0,213	0,207	0,198	0,190
150 nm	0,216	0,218	0,214	0,216	0,198	0,180
200 nm	0,213	0,216	0,212	0,204	0,194	0,183
250 nm	0,208	0,212	0,206	0,198	0,187	0,175

FIG.7

INTERNATIONAL SEARCH REPORT

Internat Application No
PCT/IB 03/05675

A. CLASSIFICATION OF SUBJECT MATTER
IPC 7 H03H9/17 H03H9/13

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 7 H03H

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

EPO-Internal, WPI Data, PAJ, INSPEC, COMPENDEX, IBM-TDB

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
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X Y	US 5 873 154 A (PARTANEN MEERI TALVILEI ET AL) 23 February 1999 (1999-02-23) column 2, line 12 - line 37 column 4, line 53 - line 67 ---	1, 2, 10-12 4, 9
Y	US 6 249 074 B1 (LIND THEODORE ET AL) 19 June 2001 (2001-06-19) column 5, line 1 - line 14 ---	4, 9
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☒ Further documents are listed in the continuation of box C.

☒ Patent family members are listed in annex.

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Date of the actual completion of the international search

15 March 2004

Date of mailing of the international search report

16/04/2004

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INTERNATIONAL SEARCH REPORT

Internat Application No
PCT/IB 03/05675

C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
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Information on patent family members

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